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COLLISIONS OF HIGH-ENERGY NUCLEAR PARTICLES WITH NUCLEI

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B. J. Moyer and G. F. Chew

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Collisions of High-Energy Nuclear Particles with Nuclei

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April 26, 1950

I. INTRODUCTION

In the first of this series of articles[1] dealing with research in high-energy nuclear physics at the University of California Radiation Laboratory the characteristic features of the synchro-cyclotron, the synchrotron, and the linear accelerator were discussed. The present article will consider the nature of the effects observed when the high-energy particles developed in the synchro-cyclotron collide with target nuclei.

A detailed discussion of the interactions between individual nucleons, and of the relation of present observations to nuclear force theories will be deferred until the next installment. Likewise, the production and properties of mesons will be treated later. Here the discussion will concern elastic and inelastic collisions of the accelerated particles with complex nuclei, and the variety of effects observed when a very energetic nuclear projectile enters a nucleus.

For a nucleon with kinetic energy in the hundreds of Mev the deBroglie wave-length is small compared to the dimensions of a heavy nucleus. Consequently it is to be expected, and is observed, that the target nucleus does not always function in the collision as an entity itself; but rather that the momentum transfers may involve only one or a few of its constituent particles, and the energies given them may be large compared to their energies of binding in the

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[1] G. F. Chew, B. J. Moyer, Am. Jour. Phys. 18, 125-135 (1950), UCRL-444.

nucleus. There are also events in which the entire energy of the incident particle is taken up by the nucleus, with the production of such a large excitation as to result in the violent ejection of several nuclear particles, or in fission into two or more fragments.

II. PRODUCTION OF HIGH-ENERGY NEUTRONS

Since the neutron experiences no interaction with matter unless it comes within the range of the nuclear forces it is an important projectile in the measurement of nuclear dimensions and in the study of nuclear forces by scattering methods. The strong yield of high-energy neutrons in the forward direction from the target of the 184-in. cyclotron provides means of investigating nuclei and nuclear force fields with a particle beam whose wave-length is sufficiently small to delineate some general features of structure. The process by which this neutron beam is produced will first be described.

At its maximum beam orbit radius the cyclotron delivers at the target either 190 Mev deuterons or 350 Mev protons. (It will also develop 380 Mev α-particles, but these are not important in production of the neutron beams here under discussion.) The character of the neutron yield in the two cases is different, as is also the predominant process by which the high-energy neutrons are produced. The case of deuteron operation will be first discussed.

A. Deuteron "Stripping"

One of the earliest observations made when the 184-in. cyclotron operations began was of the existence of an intense, relatively narrow, cone of high energy neutrons projected in the direction of the motion of the deuterons as they strike the target. The intensity and angular distribution of the neutrons was not much affected by the element of which the target was composed.

Measurements[2] of the angular distribution indicated that it decreased to

[2] A. C. Helmholz, E. McMillan, and D. Sewell, Phys. Rev. 72, 1003-1007 (1947)

half intensity at 5^{o}-6^{o} from the axis of symmetry. The energy spectrum of the neutrons was later observed by measurements on recoil protons, both by cloud chamber techniques[3] and by proportional counter telescope methods.[4] In Figure 1 are presented both angular and energy distribution data.

It is clear that these neutrons cannot originate in a compound nucleus of the target. Their origin is to be explained in terms of the unique properties of the deuteron; and the simple process, whose theory has been developed by Serber[5] and which accounts well for the observed distributions, is termed "stripping."

The deuteron is a loosely bound system, and its wave function indicates that its two particles actually spend considerable time apart from each other by distances greater than the "range" of nuclear forces. When a 190 Mev deuteron passes by a target nucleus the time interval of its interaction with the nucleus is smaller than the characteristic times of the deuteron's own internal motions. Consequently it is possible for one particle of the deuteron to interact with a target nucleus and be "stripped" from the deuteron without producing pronounced effects upon the motion of the other particle.

The energy and angular distribution of the free particle, which may be either a proton or a neutron, is then determined by its momentum at the instant of stripping. This momentum will be vectorially compounded out of the motion of the deuteron as a whole plus the relative motion of its two particles, and because of the random phases and orientations of the latter motion there will be a distribution in momentum of the free particle. Serber calculates that the half-width of the energy distribution should be about $\Delta E_{1/2} = 1.5\ (E_d \epsilon_d)^{1/2}$, where

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[3] K. Brueckner, W. Hartsough, E. Hayward, and W. Powell, Phys. Rev. 75, 555-564 (1949)

[4] See J. Hadley, et al., Phys. Rev. 75, 351-363 (1949)

[5] R. Serber, Phys. Rev. 72, 1008-1016 (1947)

E_d is the deuteron kinetic energy and ϵ_d is its binding energy. The half-angle of the angular distribution at half-intensity is $\Delta\theta_{1/2} = 1.6\ (\epsilon_d/E_d)^{1/2}$. The reason for the appearance of the binding energy rather than the actual potential well depth is just that this particular process occurs for collisions in which the deuteron particle separation is greater than the range of forces. The greatest number of neutrons will appear with just half the original kinetic energy of the deuteron; though for a thick target this will be somewhat modified by the slowing-down of some of the deuterons before the stripping event.

The comparison of theory and observation may be seen in the curves of Figure 1. The angular distribution for a uranium target is broader than the one displayed by about 15 percent, primarily because of the Coulomb deflection of the incident deuterons by the large nuclear charges. Similar distributions apply to protons from the target. The energy distribution of these has been studied by Chupp, Gardner, and Taylor,[6] by employing the cyclotron mangetic field as a proton spectrograph and distributing their detectors under the edge of the dee on a radial line through the target.

B. Neutrons Produced by 350 Mev Protons

When protons of this energy collide with nuclei it is to be expected that neutrons of highest energy in the forward direction will be produced by those events in which either a "knock-on" collision of the proton with a neutron occurs, or an "exchange" collision of the type to be described in the next article of this series. In the latter case the proton in its interaction with the nuclear particles of the target is transformed into a neutron through meson exchanges which leave it without charge.

In either of these cases the net result is to replace a neutron in the

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[6] W. Chupp, E. Gardner, and T. B. Taylor, Phys. Rev. 73, 742-749 (1948)

nucleus by a proton, and to transform a fast-moving proton into a fast-moving neutron. The resulting neutron may, in favorable cases, possess nearly all the energy of the original proton; though it is always necessary to subtract off enough energy to account for the mass difference of the initial and final nuclei.

Besides these neutrons of highest energies, there will of course be others from the many kinds of events which occur under such bombardment. But they will have lower energies and will not be so strongly concentrated in the forward direction.

The experimental determinations of the energy spectrum and angular distribution of this high-energy neutron group are not yet complete. Tentative data show the neutron energies to extend up toward 350 Mev, with a broad maximum in the neighborhood of 270 Mev. Preliminary investigations of the angular distribution of the high-energy neutrons from a Be target have been made by DeJuren, and by Wright and Miller,[7] showing a decrease to half-intensity at 25°-30° from the extended direction of the protons striking the target.

Since the nucleons with which the protons interact can have kinetic energies within the target nuclei of the order of 25 Mev, and since the exclusion principle suppresses the forward emission of protons (see Section V), it is understandable that the angular spread given to even the most energetic of the emerging neutrons will be larger than that observed for the neutrons from the stripping of deuterons.

C. Collimation of High-Energy Neutrons into a Beam

Most of the experiments with these high-energy neutrons are performed outside the 10 ft. concrete shielding wall at a distance of about 60 ft. from the cyclotron target. Neutrons escape through a carefully tapered hole in the shielding wall which aims at the target along the extended direction of the

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[7] Private communications

incident proton or deuteron beam.

The 90 Mev neutrons are attenuated in concrete with a reduction to half-intensity in about 9 1/2 inches. For the 270 Mev neutrons the half-value thickness is 18 inches. Consequently the 10 ft. of concrete would not produce as large a beam-to-background ratio as might be desired. To improve this situation a 7-ft. cube of concrete with an aligned hole is interposed between the cyclotron and the shielding wall in the direction of the neutron spray. By this means the intensity in the neutron beam defined by the collimating holes has been measured in the 90 Mev case to be a few thousand times that at a point one centimeter outside the geometrically defined beam volume. For the 270 Mev neutrons the ratio is not well known, but it is not this favorable.

Flux densities of the order of 10^6 per cm^2 per sec. are available with 90 Mev mean energy, and 10^4 per cm^{+2} per $sec.^{-1}$ for 270 Mev mean energy. In Figure 2 a plan view of the neutron beam system is shown.

III. COLLISIONS OF HIGH-ENERGY NEUTRONS WITH NUCLEI

Before proceeding to further discussion of effects produced in nuclei of the cyclotron target by incidence of the proton or deuteron beam, a section will be devoted to description of some features of the collisions of the high-energy neutrons with nuclei. Much to be said here will apply equally well to collisions of protons and deuterons with nuclei except for the effects, such as Rutherford scattering, which depend specifically upon electrical charge.

A collision is defined as any interaction of a neutron in flight with a nucleus in its path which results in changing observably the state of motion of the neutron. Collision types may be subdivided into elastic and inelastic events, and these will be described in subsequent sections. The total cross sections presented by various nuclei for a collision of any type will first be discussed.

A. Total Collision Cross Sections and Nuclear "Transparency"

The measurement of total cross section is made by observing the reduction in intensity of a directed beam of high-energy neutrons by known thicknesses of matter placed between the neutron source and a detector of the neutrons in the beam. If the experiment is properly designed, any collision event which either deflects, degrades, or absorbs a neutron will result in eliminating it from possibility of actuating the detector. Correction must be made for the neutrons which are scattered by sufficiently small angles to still strike the detecting volume, but good experimental arrangements make this a very small effect.

Two types of high-energy neutron detectors have been employed. Cook, et al,[8] used small carbon discs in which neutrons of over 20 Mev energy produce the $C^{12}(n,2n)C^{11}$ reaction yielding the 20.5 minute half-life positron emission. DeJuren and Knable[9] used chambers in which pulses from fission of bismuth nuclei by neutrons of over 50 Mev energy were counted. The energy dependence of the detectors and the energy distribution in the neutron beam make the effective neutron energy in the case of carbon detectors about 84 Mev, and in the case of bismuth fission detection about 95 Mev. In Figure 2 may be seen the arrangements of the DeJuren and Knable experiment.

The nuclear radii deduced from this experiment are plotted in Figure 3. Deduction of radii from cross sections must be done in terms of some model of the nucleus. If an "opaque" model is assumed, i.e., a sphere which is perfectly absorbing toward the wave system describing the neutron beam, then the total cross section presented by a nucleus of radius R is

$$\sigma_T = 2\pi R^2 \qquad (1)$$

The factor of 2 can be related to the familiar Babinet's principle of

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[8] L. Cook, E. McMillan, J. Peterson, and D. Sewell, Phys. Rev. 75, 7 (1949)

[9] J. DeJuren and N. Knable, Phys. Rev. 77, 606-614 (1950)

physical optics which leads to the conclusion that when an advancing wave disturbance meets an opaque obstacle the total intensity of the diffracted disturbance is equal to that which is absorbed. Thus the cross section for elastic scattering of the neutrons, which will be represented by diffraction of their wave system, will be equal to the cross section for "absorption," meaning any interaction other than elastic scattering. But since at this neutron energy the geometrical area presented by the nucleus must define the absorption cross section, it follows that the total collision cross section will be twice this value.

Since the density of nuclear matter is thought to be constant, it is to be expected on the basis of an opaque model of the nucleus that total cross sections would be proportional to $A^{2/3}$, where A is the atomic number, and that nuclear radii deduced by relationship (1) would be proportional to $A^{1/3}$. The plot of R vs $A^{1/3}$ in Figure 3 indicates the way in which experimental results deviate from the opaque model predictions (see dashed line with x's). The results for large A approach the above description, showing a tendency to become proportional to $A^{1/3}$, but for the nuclei below $A \simeq 60$ the simple opaque model theory is not an accurate representation.

An interesting interpretation of this discrepancy is provided by the "transparent" nuclear model of Fernbach, Serber, and Taylor.[10] The volume of space occupied by the nucleus is considered to possess an "absorption coefficient" for the neutron wave. From a particulate point of view this is equivalent to saying that a high-energy neutron will have a certain mean free path in nuclear matter with respect to collisions with the constituent nucleons.

Not only will nuclear matter possess an absorption coefficient, but it will also display an "index of refraction" for the neutron wave by which phase displacements for the penetrating wave relative to the unperturbed wave will occur.

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[10] S. Fernbach, R. Serber, and T. B. Taylor, Phys. Rev. 75, 1352-1355 (1949)

This effect is of course due to the change in potential of the field in which the neutron moves as it enters or leaves the nuclear volume.

By selecting appropriate values for these two parameters, and then using the mathematical relationships of the transparent model theory to calculate nuclear radii from the observed values of σ_T, the close proportionality of R to $A^{1/3}$ shown in the indicated curve of Figure 3 is obtained. The absorption coefficient employed for the case of 84 Mev neutrons was 2.2×10^{12} cm^{-1}, corresponding to a mean free path of 4.5×10^{-13} cm. For the 95 Mev case which is shown in Figure 3 these values were 3.0×10^{12} cm^{-1}, and 3.3×10^{-13} cm.

The value of σ_T for neutrons of 270 Mev mean energy have not yet been published. Measurements indicate that they are approximately 0.6 of the values at 95 Mev. Transparency effects are presumably much more pronounced at this energy.

B. <u>Elastic Scattering of Neutrons at 84 Mev</u>

It was mentioned above that in the opaque nuclear model the cross section for elastic scattering should be one-half the total collision cross section. Moreover, the angular distribution of the elastically scattered neutrons should be described by the Fraunhofer diffraction pattern of a plane wave encountering a perfectly absorbing sphere. This is approximately the same as the Fraunhofer pattern for a circular disc, which is:

$$I(\theta) \sim \left[\frac{J_1 (K R \sin \theta)}{\sin \theta} \right]^2 ,$$

where J_1 is the first order Bessel Function, and $K = \frac{1}{\lambda}$ is the propagation constant for the incident wave system.

A study[11] of the angular distribution has given results similar to the central maximum of the Fraunhofer pattern, but departing somewhat in a manner which is qualitatively expected from the transparent model. Figure 4 illustrates

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11 A. Bratenahl, S. Fernbach, R. H. Hildebrand, C. E. Leith, and B. J. Moyer, Phys. Rev. 77, 597-605 (1950)

the comparison with opaque model predictions.

By integrating the differential scattering curves a value for the elastic scattering cross section is obtained which is always slightly greater than 0.5 σ_T. This also is predicted by the transparent model.

Complementary measurements of the cross sections for inelastic collisions have yielded values always a few percent less than 0.5 σ_T. These measurements are made in the broad neutron beam ahead of the collimator system and are so designed that elastic scattering events do not remove neutrons from detectability. The reduction of detected neutrons is then solely due to events which absorb the neutrons or degrade their energy below the detection threshold.

IV. NUCLEAR DISINTEGRATION TYPES AT HIGH ENERGIES

The effects produced when the cyclotron projectiles or the high-energy neutrons enter target nuclei include a great variety of events. They will here be discussed under such classifications as "spallation," fission, and knock-on collisions with constituent nuclear particles.

A. Nuclear Chemistry; Spallation and Stars

Chemical identification of radioactive reaction products has shown results which are frequently difficult to classify by stating the incident particle and the expelled particles in the usual form, e.g. (p,α), etc. For the emitted particles may include in total several protons and neutrons, and it is not possible by chemical means to judge whether the emitted nucleons came away singly or in units such as H^2, H^3, He^3, He^4, etc. Emission of fragments as large as Li^8 has been identified by film track and cloud chamber studies.

For the purposes of indicating such reactions, Seaborg, Perlman, and their associates have adopted a symbolism such as

$$_{33}As^{75}(d, 9p12n)_{25}Mn^{56},$$

which is understood to enumerate the ejected nucleons but not necessarily show the form in which they are emitted. Such reactions have been termed "nuclear spallation."

For examples of spallation effects, reference can be made to the study of Miller, Thompson, and Cunningham[12] who found from the bombardment of Cu with 190 Mev deuterons radioactive products distributed from ${}_{15}P^{32}$ to ${}_{30}Zn^{63}$. A striking array of products was observed by O'Connor and Seaborg[13] from the bombardment of U^{238} with 380 Mev alpha-particles. Through the processes of fission and spallation a continuous distribution of products was produced extending down to Z = 25 (Mn). It is estimated that mass numbers down to about 180 are due to spallation, and those lower to fission.

The discovery[14] of the delayed emission of neutrons from production of N^{17} provided a simple means of studying the yields of spallation reactions leading to N^{17} from elements lying above it in atomic number. Chupp and McMillan[15] have studied the relative yields of N^{17} from various elements and isotopes under bombardment by 190 Mev deuterons extending as far as sulphur and were able to show systematic effects such as augmented yields for those cases where emission of alpha-particles by the compound nucleus could lead to N^{17}.

Graphic portrayals of nuclear spallation may be seen in the cloud chamber photographs of nuclear "stars" produced by the high-energy neutrons. Figure 5 is one such a photograph among many obtained by W. M. Powell[16] and his associates. Figure 6 shows a nuclear star in photographic emulsion in which one of the ejected fragments is a Li^8 nucleus, which subsequently decays (half-life = 0.88

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[12] D. R. Miller, R. C. Thompson, and B. B. Cunningham, Phys. Rev. 74, 347-348 (1948)

[13] P. R. O'Connor and G. T. Seaborg, Phys. Rev. 74, 1189-1190 (1948)

[14] N. Knable, E. O. Lawrence, C. E. Leith, B. J. Moyer, and R. L. Thornton, Phys. Rev. 74, 1217 (1948)

[15] Yet to be published

[16] W. M. Powell, Phys. Rev. 72, 739 (1947)

sec.) into a Be^8 nucleus, which immediately divides into two alpha-particles.

Systematic studies of the number, type, and distribution of star prongs have been made by Gardner and Peterson,[17] from which some information may be inferred about the excitation energy of the bombarded nuclei. Ejected neutrons of course leave no tracks, and estimates of their number and energies must be attempted.

B. High-Energy Fission

Fission by high-energy bombardment displays notable differences from the familiar slow-neutron fission. Kelly and Wiegand[18] identified fission by the 90 Mev neutron beam in elements ranging from Pt to Bi and measured the relative fission cross sections. They determined the threshold for fission of Bi by neutrons to be approximately 50 Mev, and this has served since as a convenient means of detecting neutrons of greater energies than this (see Section III-A).

The mass distribution of fission fragments in high-energy fission is strikingly different from that in the slow-neutron case. O'Connor and Seaborg[13] and Goeckermann and Perlman[19] have made extensive chemical identifications of high-energy fission products from U and Bi. The most probable partition of the parent nucleus is into two equal fragments, in contrast to the asymmetric character familiar with slow fission. Moreover, the mass number of these most probable fragments is not one-half the mass number of the original bombarded nucleus, but is distinctly less than this value; whereas the atomic number of these fragments is one-half that of the bombarded nucleus. This suggests that the parent nucleus in the fission event is a neutron-deficient isotope of the bombarded element, formed by evaporating approximately 12 neutrons from the bombarded

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[17] E. Gardner and V. Peterson, Phys. Rev. 75, 364-369 (1949)
E. Gardner, Phys. Rev. 75, 379-382 (1949)

[18] E. Kelly and C. Wiegand, Phys. Rev. 73, 1135-1139 (1948)

[19] R. H. Goeckermann and I. Perlman, Phys. Rev. 73, 1127-1128 (1948)

nucleus before fission occurs.

Another notable feature is that the n-p ratio in the fragments is the same as that of the parent nucleus. This means that when fission into fragments of unequal mass occurs, the lighter fragment will possess an excess of neutrons and will most often be β^- active, whereas the heavier fragment will be deficient in neutrons and will usually be β^+ active. This again is in contrast to the slow fission situation for which all fragments have typically an excess of neutrons. The inference from this is that the fission process is fast in the high-energy case and that the parent nucleus is highly excited even after considerable energy has been dissipated in the preceding "boiling-off" of 10 to 12 neutrons.

Fission of thorium induced by 40 Mev alpha-particles from the 60-in. Crocker Laboratory cyclotron has been studied by A. S. Newton.[20] Here the partition of the nucleus displays the characteristic asymmetry in the relative yields of products, but the ratio of peak to valley yields is only about 2, as compared to 600 for slow neutron fission of uranium. The processes characteristic of high-energy fission are in evidence here, though the excitation of the parent nucleus is not so high as to prevent evidence of some rearrangement into the energetically favorable distributions which give the double hump.

C. <u>Ejection of Fast Particles; Sub-Nuclear Collisions</u>

1. Emission of Deuterons and Tritons

Upon beginning a study with proportional counters of the emission of high-energy protons from nuclei under bombardment by the 90 Mev neutron beam, York and Hadley[21] discovered an unexpected yield of energetic deuterons strongly concentrated in the forward direction. The same observation was made almost

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[20] A. S. Newton, Phys. Rev. 75, 17-29 (1949)

[21] H. York, Phys. Rev. 75, 1467 (1949)
J. Hadley and H. York, to be published in Phys. Rev., UCRL-359 Revised

simultaneously in cloud chamber studies by Brueckner and Powell,[22] and subsequently by Bradner[23] using film track methods.

The reason for this being unexpected lies in the fact that the deuteron is such a loosely-bound system. In order for a deuteron to emerge it would be necessary for a proton and a neutron in the nucleus to receive relative momenta appropriate to those in a deuteron, together with a total momentum sufficiently great to give a fair probability of penetrating through nuclear matter to the surface without further collision. The likelihood of accomplishing this by nuclear excitation or by knock-on collisions with sub-units of the nuclear system seems at first thought remote.

Further light is shed upon the mechanism by the fact that the angular distribution is strongly peaked forward, and by the observation that the deuterons emerging directly forward have an energy distribution with a peak at 60-65 Mev and a width at half-intensity of about 25 Mev. It is clear that the mechanism will not involve a compound nucleus, but rather a sub-nuclear interaction between the bombarding neutron and a constituent proton.

Chew and Goldberger[24] were able to give quite a satisfactory explanation of a mechanism by which these deuterons are produced. The nucleons within a nucleus are in motion, and their kinetic energies will extend as high as about 25 Mev. Now when a bombarding neutron penetrates through the nucleus there is a significant probability that a proton within the nucleus can be moving with direction and speed so related to the neutron as to correspond to a state of motion of a deuteron. The two particles then continue together as a deuteron, and if the subsequent path within the nucleus is not large it can emerge intact.

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[22] K. Brueckner and W. M. Powell, Phys. Rev. 75, 1274 (1949)

[23] H. Bradner, Phys. Rev. 75, 1467 (1949)

[24] G. F. Chew and M. L. Goldberger, Phys. Rev. 77, 470-475 (1950)

It is now clear why these deuterons are strongly peaked in the forward direction and show a rather high average energy. Only those protons with large momenta parallel to the neutron direction will be captured. Consequently a deuteron thus formed can be moving only within a very narrow angular range about the direction of the neutron, and its momentum compounded out of that of the neutron and proton will forbid a low kinetic energy.

A numerical example will illustrate. In Figure 7 are pictured a 100 Mev neutron and a 25 Mev proton; the former represents a bombarding neutron moving through a nucleus, and the latter one of the nuclear protons. The neutron momentum is (non-relativistically) $p_n = \sqrt{2mE_n} = 10f\sqrt{2m}$, since $E_n = 100$ Mev, and f is a factor to adjust the units. The proton momentum is $p_p \sim 5f\sqrt{2m}$. The momentum of each relative to their center of mass is $2.5f\sqrt{2m}$, so that the kinetic energy of each relative to the center of mass is only 6.25 Mev. So from the standpoint of internal kinetic energy, the combination of these two particles to form a deuteron need not be forbidden.

If their relative orbits were such as to agree with an allowed state of the deuteron, its momentum would be,

$$p_d = p_n + p_p = 15f\sqrt{2m} = \sqrt{2(2m)E_d} .$$

Its kinetic energy, E_d would then be 112 Mev, and upon emerging from the nuclear potential well its observed energy may be about 95 Mev.

York's measurements indicate that about 1/12 of all inelastic collisions of 90 Mev neutrons with carbon nuclei result in deuteron ejection. For lead nuclei the fraction is approximately 1/25.

Besides deuterons, a much smaller number of tritons is also observed in the forward direction with energies between 35 and 70 Mev. Some such "pick-up" process must also operate to produce these, in which the incident nucleon and <u>two</u> of the target nucleons just happen to have momenta relative to each other which are compatible with the internal motion of a triton.

2. Knocking-Out of Protons

The Hadley-York experiment,[21] and the cloud chamber observations,[22] on the protons emerging from struck nuclei demonstrate energies extending up to well over 100 Mev, and angular distributions concentrated so strongly forward as to lead to the conviction that they arise predominantly from n-p collisions within the nuclei. This at least can be stated for those protons emerging with energies in excess of 20 Mev.

For protons knocked out of carbon into differentials of solid angle at various angles the energy spectra are portrayed in Figure 8. York finds that in 0.4 of the cases of inelastic collision of 90 Mev neutrons with carbon nuclei, protons of energy greater than 20 Mev emerge. For copper and lead these fractions are 0.31 and 0.24, respectively. Cloud chamber pictures also demonstrate that of the energy dissipated in matter by the passage of high-energy neutrons, a large fraction is represented in the production of energetic protons. This is of significance in estimating the biological effects of such neutrons.

Though these protons originate in n-p collisions within the nucleus, it must not be presumed that the energy and angle distributions are representative of free n-p scattering. For a proton within the nucleus is not at rest, but has momentum which must be vectorially compounded with that contributed by the neutron in the collision. In addition the Pauli principle acts to prevent small momentum transfers, as will be described in the following section. Also there may have been prior collisions of the neutron in the nucleus, and subsequent collisions of the proton before it emerges.

V. DYNAMICS OF NUCLEAR COLLISIONS AT HIGH ENERGIES

In a brief article published[25] in the early days of the operation of the 184-in. cyclotron Serber outlined some outstanding features to be expected of

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[25] R. Serber, Phys. Rev. 72, 1114-1115 (1947)

collisions of high-energy nuclear projectiles with nuclei. Many of these features have been exemplified by experiments described in this paper. A condensed summary of the physical ideas involved is now presented.

1. The interaction time for a collision between the projectile and a nucleon is small compared to the time between collisions of particles within the nucleus. Hence the nucleus as a system does not "know" of the collision until after it has occurred. This same feature was previously presented in terms of the ratio of nuclear size to the wave-length for the projectile beam.
2. Since the collision cross section between nucleons decreases with relative energy, it is to be expected that nuclei will demonstrate transparency for high-energy particles. For 90 Mev neutrons the mean free path in nuclei has been seen to be about 4×10^{-13} cm.
3. The momentum transfers to struck nucleons are not usually large compared to characteristic momenta of nucleons in nuclei. Hence the observed angular and energy distributions will not be described by free-particle collisions.
4. Very small momentum transfers are suppressed by the exclusion principle on these grounds: if nuclear matter is represented by a Fermi gas bounded by the nuclear volume, then all momentum states are occupied up to a certain maximum value. Thus only those collisions are allowed which will transfer sufficient momentum to lead to an unoccupied state.
5. In large nuclei the incident and struck nucleons will usually have further collisions before emerging. The energy is thus distributed over the nucleus, resulting in excitation which is relieved by the boiling-off of many particles and producing the spallation reactions.
6. In light nuclei the energy delivered will be largely carried off by

relatively few particles, such as knocked-out protons and "pick-up" deuterons.

In the next paper of this series the discussion will concern free-particle scattering experiments at high energy and their bearing upon nuclear forces.

This work was performed under the auspices of the Atomic Energy Commission.

FIGURE CAPTIONS

Figure 1. (a) Angular distribution of neutrons produced by deuteron "stripping" at a copper target (from reference 2).

(b) Energy distribution of neutrons from 190 Mev deuterons striking a 1/2-in. Be target. The shaded rectangles and the vertical lines are data from two experimental methods, and the curve is from Serber's theory (see references 4 and 5).

Figure 2. Plan view of neutron beam collimating system.

Figure 3. Nuclear radii as deduced from measurements of total cross sections. Dashed curve arises from theory of opaque nucleus. Solid curve is from transparent nucleus theory (see reference 10).

Figure 4. Angular distribution of neutrons elastically scattered from aluminum nuclei. The dashed curve is the distribution predicted by the opaque nucleus theory, and the dotted curve by the transparent nucleus theory.

Figure 5. Cloud Chamber photograph of nuclear star induced by high-energy neutron. Magnetic field aids in identifying particles by measurement of $B\rho$. (Photograph from W. M. Powell).

Figure 6. Neutron-induced nuclear star in photographic emulsion showing ejection of a Li^8 nucleus. The heavy track projected downward and to the right is the Li^8, which subsequently disintegrates into two alpha-particles moving in opposite directions.

Figure 7. Representation of formation of deuteron by neutron-proton "pick-up" within nucleus. Point C is the center of mass for a high-energy neutron N and a nuclear proton P. The vectors represent momenta.

Figure 8. Energy spectra for protons knocked out of carbon nuclei at various angles by 90 Mev neutrons (see reference 21 for details and probable errors).

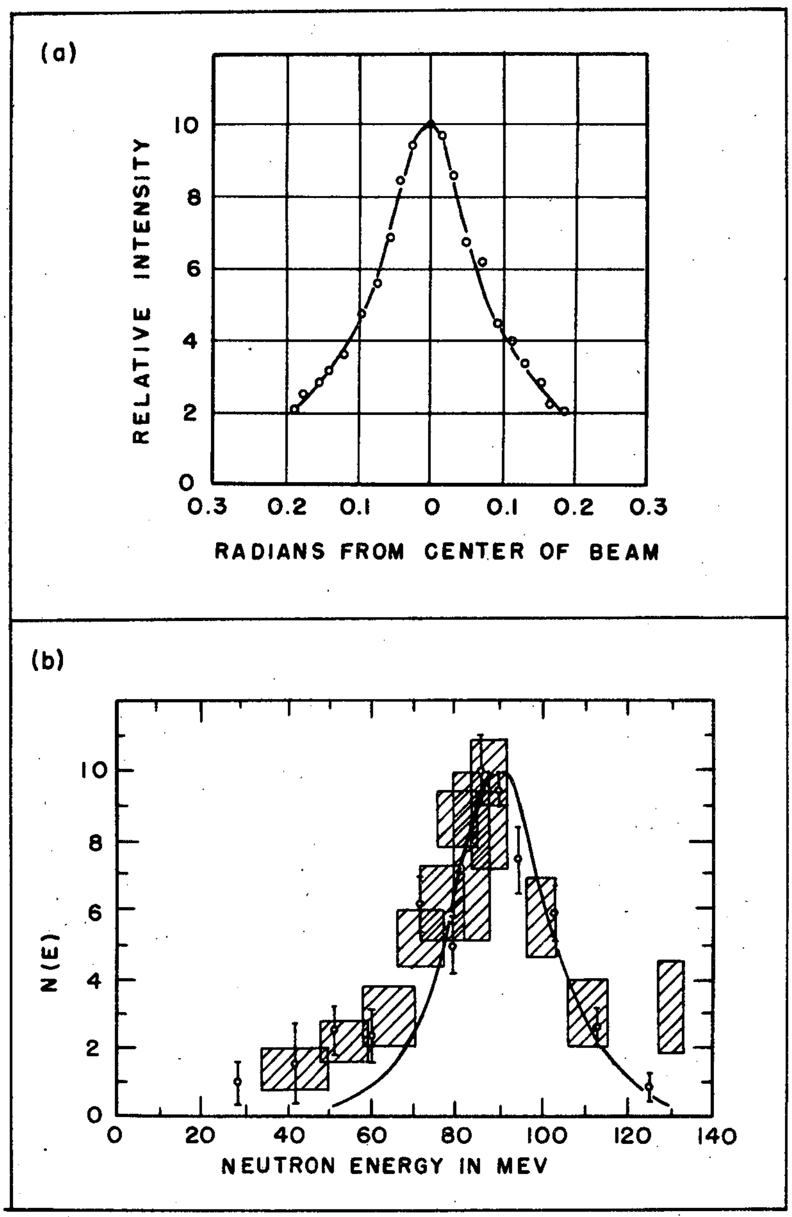

(a)
RELATIVE INTENSITY
10
8
6
4
2
0
0.3 0.2 0.1 0 0.1 0.2 0.3
RADIANS FROM CENTER OF BEAM
(b)
N(E)
10
8
6
4
2
0
0 20 40 60 80 100 120 140
NEUTRON ENERGY IN MEV

FIG. 1

Mu 161

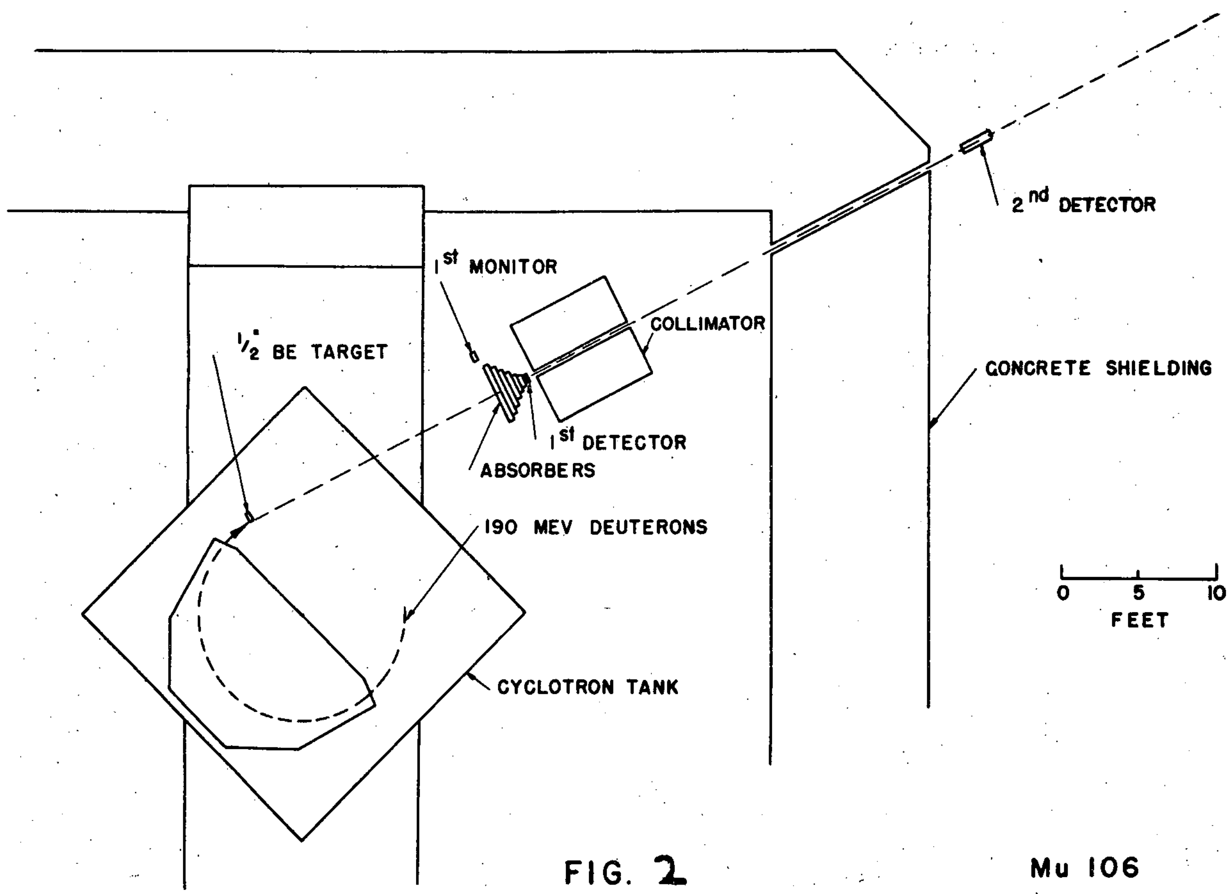
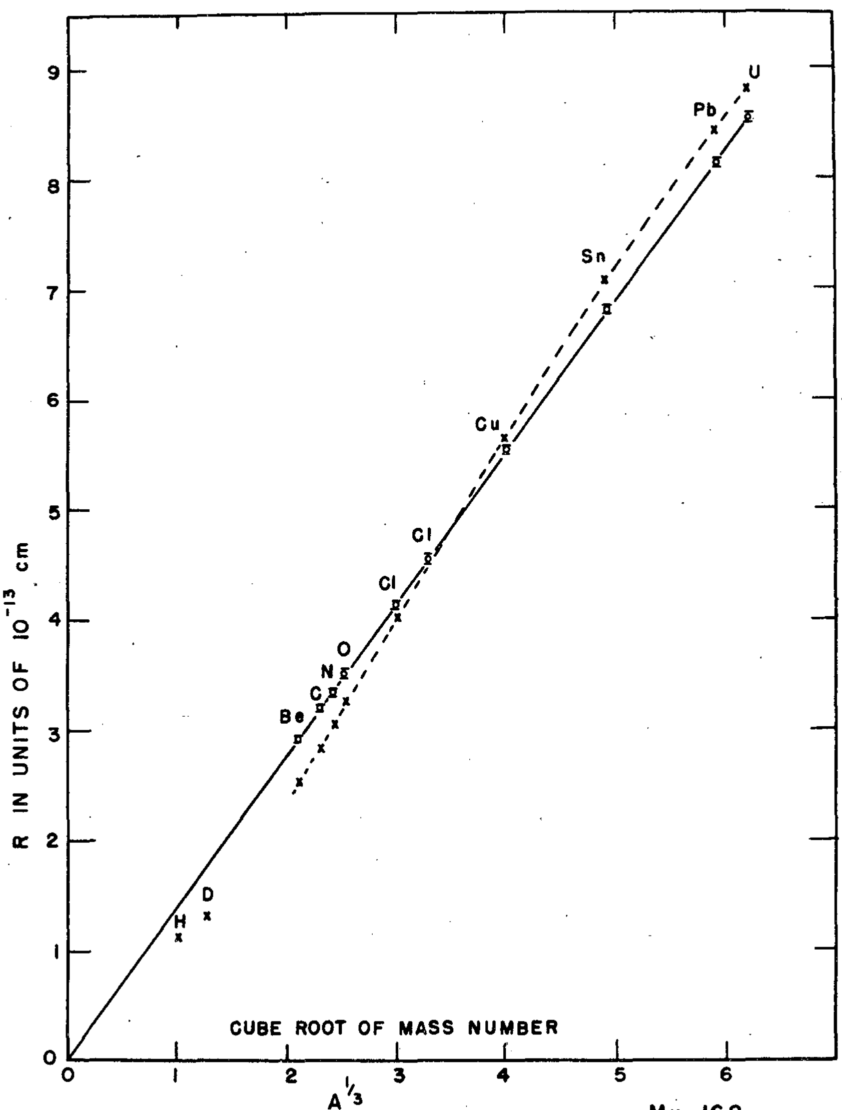

2 nd DETECTOR
1 st MONITOR
COLLIMATOR
1/2" BE TARGET
CONCRETE SHIELDING
1 st DETECTOR
ABSORBERS
190 MEV DEUTERONS
0 5 10
FEET
CYCLOTRON TANK

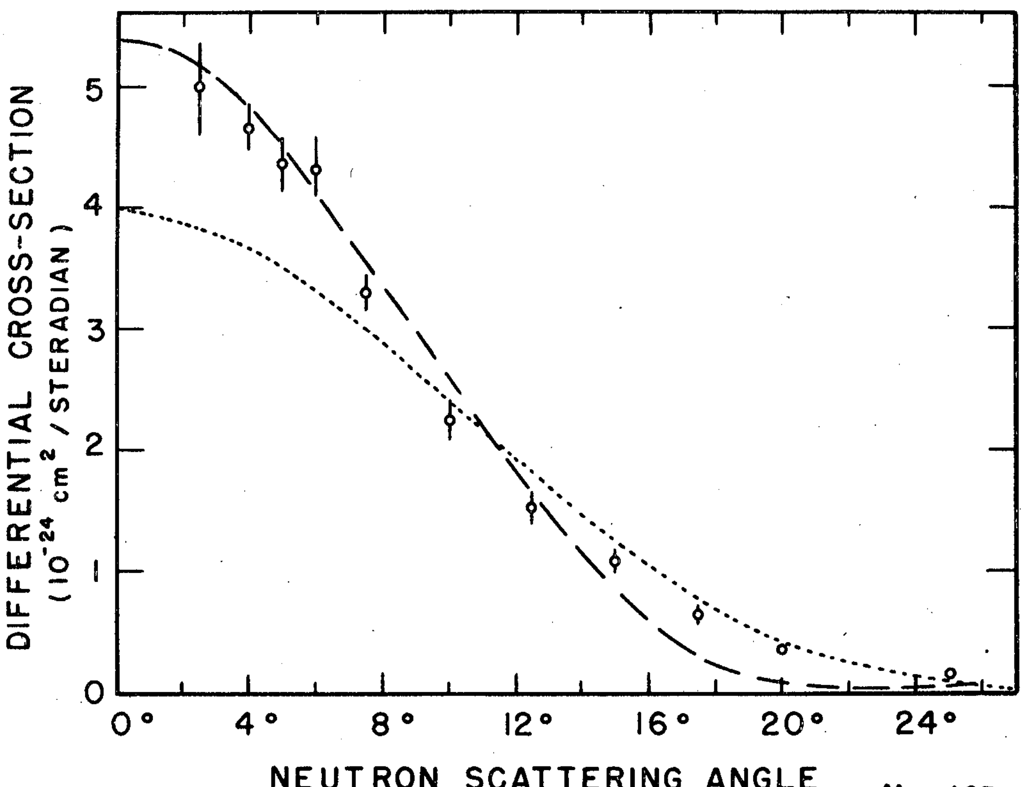
FIG. 2

Mu 106


R IN UNITS OF 10^{-13} cm
CUBE ROOT OF MASS NUMBER
$A^{1/3}$
U
Pb
Sn
Cu
Cl
Cl
O
N
C
Be
D
H
0
1
2
3
4
5
6
7
8
9

Mu 162

FIG. 3



DIFFERENTIAL CROSS-SECTION
(10^-24 cm^2 / STERADIAN)
5
4
3
2
1
0
0°
4°
8°
12°
16°
20°
24°
NEUTRON SCATTERING ANGLE

Mu 163

FIG. 4

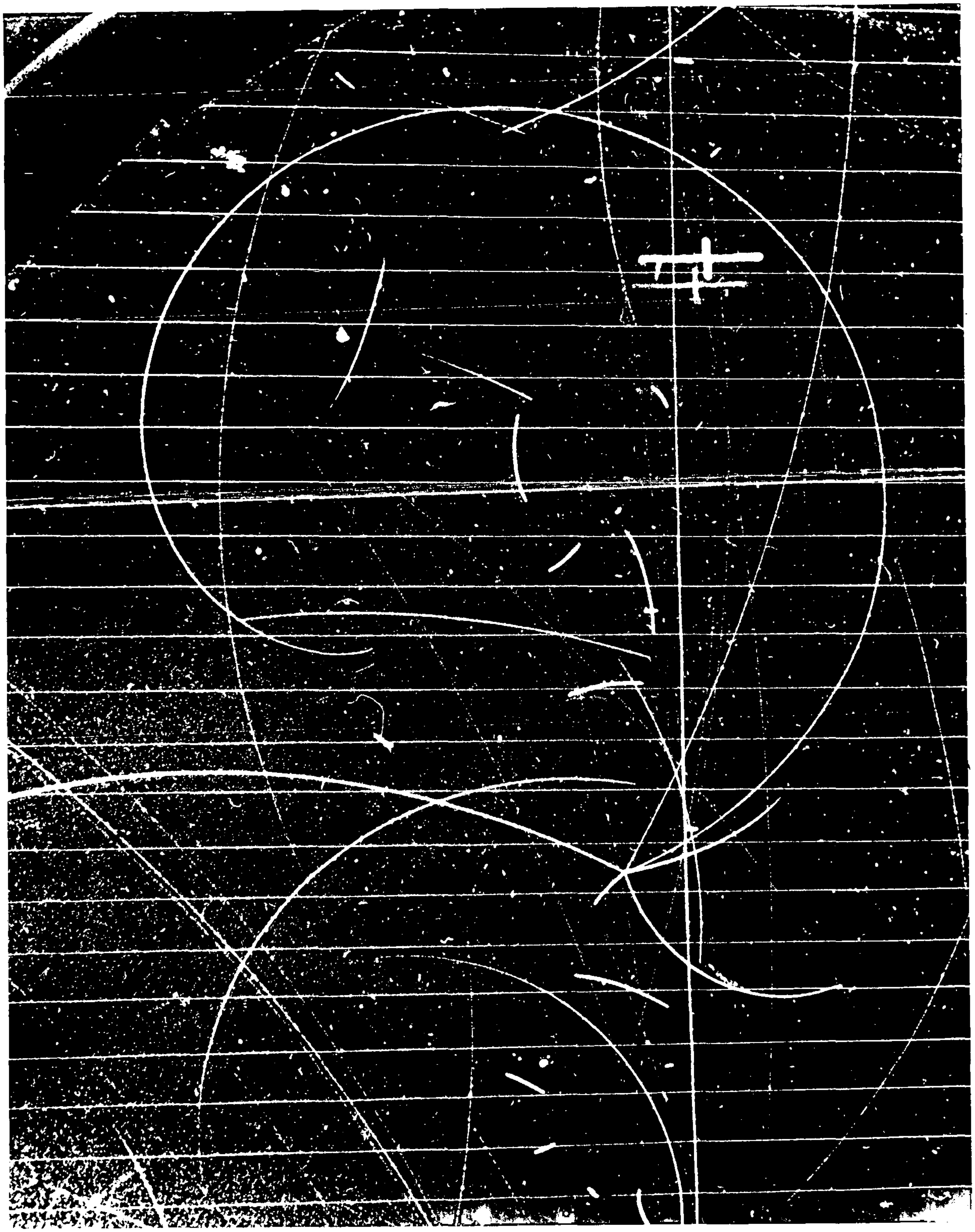
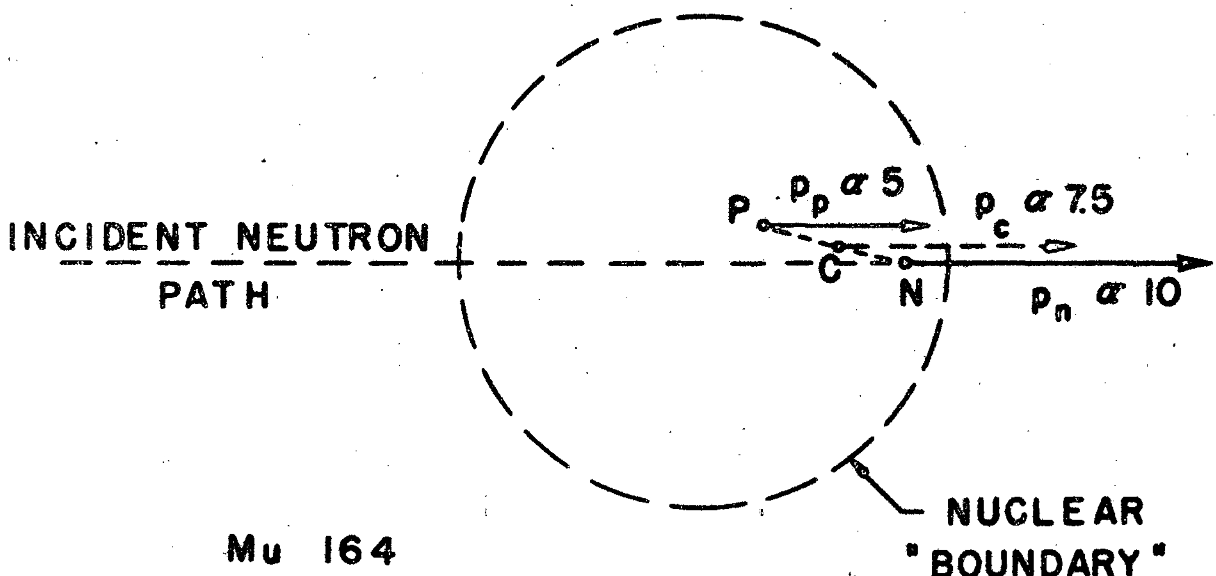


FIG. 5



INCIDENT NEUTRON PATH
P
$p_p \propto 5$
$p_c \propto 7.5$
C
N
$p_n \propto 10$
NUCLEAR "BOUNDARY"

Mu 164

FIG. 7

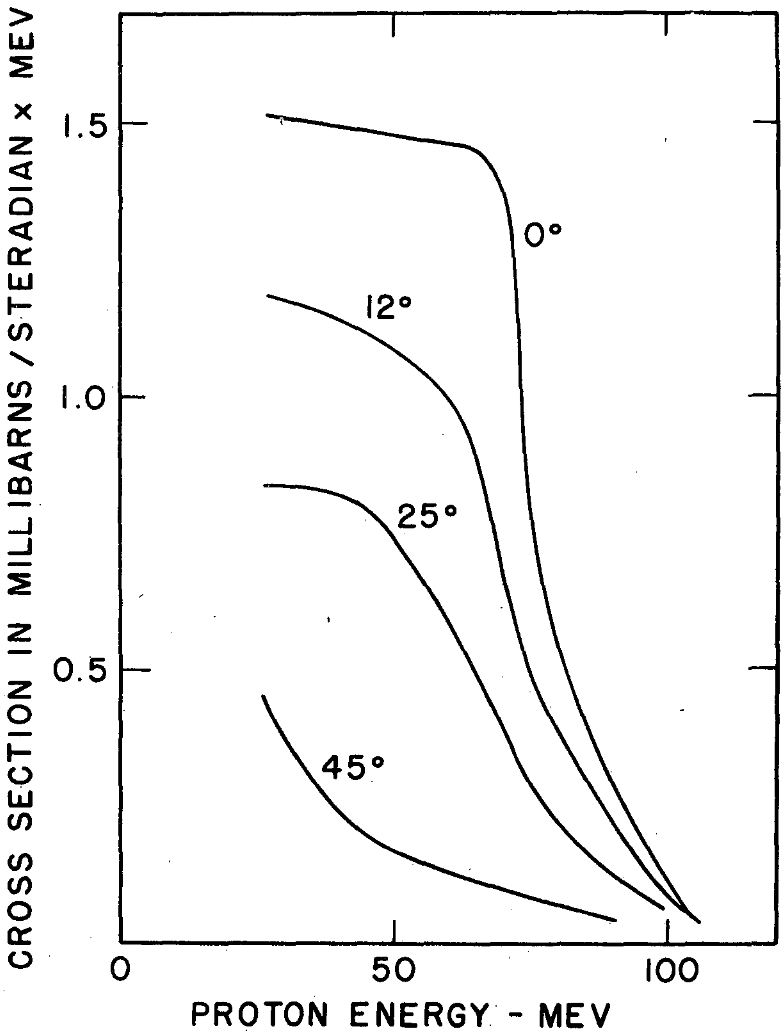

CROSS SECTION IN MILLIBARNS / STERADIAN × MEV
1.5
1.0
0.5
0°
12°
25°
45°
0
50
100
PROTON ENERGY - MEV

FIG. 8

MU 165